AFRL-OSR-VA-TR-2013-0019

(YIP 09) Quantum Engineering of Strongly Correlated Matter with Ultracold Fermi Gases

PROF MARTIN W ZWIERLEIN

Massachusetts Institute of Technology

May 2013
Final Report

AIR FORCE RESEARCH LABORATORY
AF OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
ARLINGTON, VIRGINIA 22203
AIR FORCE MATERIEL COMMAND

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
19-03-2012	Final	01-Jul-10 TO 30-Jun-2011

4. TITLE AND SUBTITLE
(YIP 09) Quantum Engineering of Strongly Correlated Matter with Ultracold Fermi Gases

5a. CONTRACT NUMBER
FA9550-10-1-0337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
PROF MARTIN W ZWIERLEIN

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
875 North Randolph St.
Arlington VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR/RSE

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-OSR-VA-TR-2013-0019

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This is the final report on the Young Investigator Program (YIP), which is currently being continued as a Presidential Early Career Award for Science and Education (PECASE). In this program, we aim at realizing model systems of strongly correlated, disordered electrons using ultracold fermionic atoms stored in an optical "crystal". The general theme is to study high-temperature superfluids, Fermi liquids ("metals") and insulators in the presence of disordered impurities whose influence on the fermions can be controlled. In the one-year funding period of the YIP, we have completed and exceeded the goals set for year 1 of the program: We studied spin transport in strongly interacting Fermi gases by watching the motion of impurities, so-called Fermi Polarons, through a Fermi sea of atoms; we have simultaneously immersed two different kinds of fermionic impurities of differing mass in a Bose-Einstein condensate, that provides a phonon background analogous to that in a crystal. Furthermore, we have performed a theoretical study on localized magnetic impurities in a superfluid of paired ultracold fermions.

15. SUBJECT TERMS
Ultracold Atoms, Fermi Gases, Strong Interactions, Strongly Correlated Materials, Quantum Simulators, Superconductivity

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
UU	UU		SAR	8	

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Quantum Engineering of Strongly Correlated Matter with Ultracold Fermi Gases

AFOSR Young Investigator Program
Final Report
July 2010 – June 2011

Martin W. Zwierlein

Abstract

This is the final report on the Young Investigator Program (YIP), which is currently being continued as a Presidential Early Career Award for Science and Education (PECASE). In this program, we aim at realizing model systems of strongly correlated, disordered electrons using ultracold fermionic atoms stored in an optical "crystal". The general theme is to study high-temperature superfluids, Fermi liquids ("metals") and insulators in the presence of disordered impurities whose influence on the fermions can be controlled.
In the one-year funding period of the YIP, we have completed and exceeded the goals set for year 1 of the program: We studied spin transport in strongly interacting Fermi gases by watching the motion of impurities, so-called Fermi Polarons, through a Fermi sea of atoms; we have simultaneously immersed two different kinds of fermionic impurities of differing mass in a Bose-Einstein condensate, that provides a phonon background analogous to that in a crystal. Furthermore, we have performed a theoretical study on localized magnetic impurities in a superfluid of paired ultracold fermions.

1. Universal Spin Transport in a Strongly Interacting Fermi Gas

Ariel Sommer, Mark Ku, Giacomo Roati, and Martin W. Zwierlein

Nature 472, 201-204 (2011)

Transport of fermions is central in many fields of physics. Electron transport runs modern technology, defining states of matter such as superconductors and insulators. Transport of electron spin, rather than of charge, is being explored as a new way to carry information. Neutrino transport energizes supernova explosions following the collapse of a dying star, and hydrodynamic transport of the quark-gluon plasma governed the expansion of the early Universe. However, our understanding of non-equilibrium dynamics in such strongly interacting fermionic matter is still limited. Ultracold gases of fermionic atoms realize a pristine model for such systems and can be studied in real time with the precision of atomic physics. It has been established that even above the superfluid transition such gases flow as an almost perfect fluid with very low viscosity when interactions are tuned to a scattering resonance. However, in this work we show that spin currents, as opposed to mass currents, are maximally damped, and that interactions can be strong enough to reverse spin currents, with opposite spin components reflecting off each other. We determine the spin drag coefficient, the spin diffusivity, and the spin susceptibility, as a function of temperature on resonance and show that they obey universal laws at high temperatures. At low temperatures, the spin diffusivity approaches a minimum value set by h/m, the quantum limit of diffusion, where h is Planck's constant and m the atomic mass. For repulsive interactions, our measurements appear to exclude a metastable ferromagnetic state.

This work was featured in a [Physics Today] article, June 2011, by Barbara Gross-Levi, as well as in a [Nature News&Views article by John Thomas].

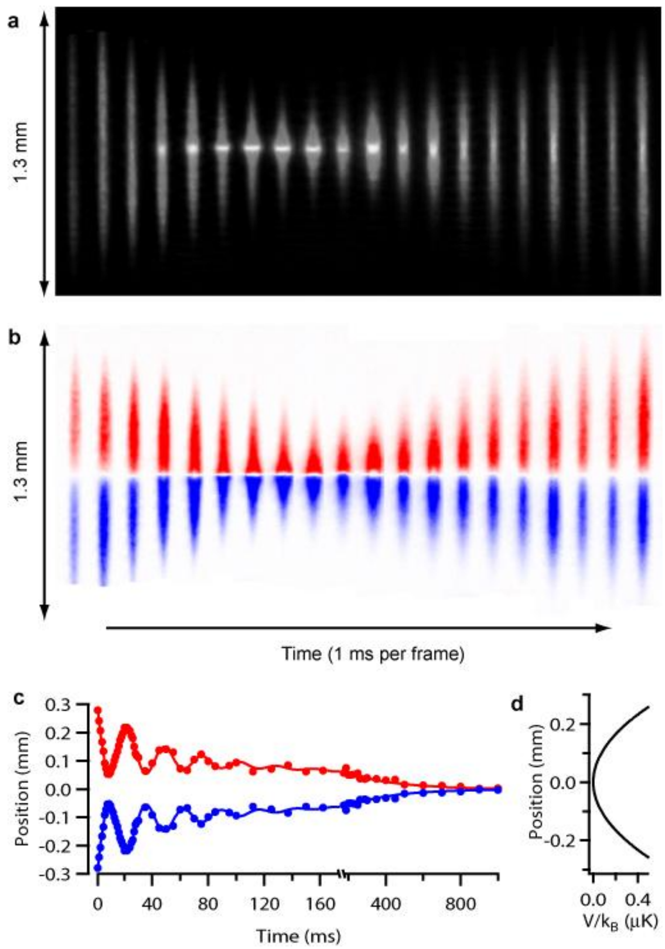

Figure 1 Observation spin reflection in a resonant collision between two oppositely spin-polarized clouds of fermions. a) shows the total column density and b) the difference in column densities of the two clouds (red: spin up, blue: spin down), after the magnetic field is set to the Feshbach resonance. The collision leads to the formation of a high-density interface between the two spin states. c) The separation between the centers of mass of the two spin states initially oscillates at a frequency of 1.63(2) nz, where nz = 22.8 Hz is the axial trap frequency. Even after half a second, there is still substantial spin separation. The diffusion time indicates a diffusivity on the order of h/m. d) Shows the harmonic trapping potential along the axis of symmetry.

2. Universal Spin Transport in Polaronic and Superfluid Fermi Gases

Ariel Sommer, Mark Ku, and Martin W. Zwierlein,

New Journal of Physics 13, 055009 (2011)

In this work, we present measurements of spin transport in ultracold gases of fermionic Lithium-6 in a mixture of two spin states at a Feshbach resonance. In particular, we study the spin-dipole mode, where the two spin components are displaced from each other against a harmonic restoring force. We prepare a highly imbalanced, or polaronic, spin mixture with a spin-dipole excitation and we observe strong, unitarity-limited damping of the spin-dipole mode. In gases with small spin imbalance, below the Pauli limit for superfluidity, we observe strongly damped spin flow even in the presence of a superfluid core. This indicates strong mutual friction between superfluid and polarized normal spins, possibly involving Andreev reflection at the superfluid–normal interface.
This work was chosen as an IOP Select for the NJP Focus issue on Strongly Correlated Quantum Fluids: From Ultracold Quantum Gases to QCD Plasmas.

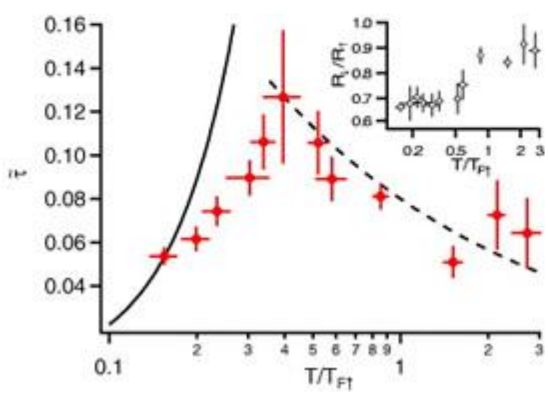

Figure 2 Spin Transport in Spin-Imbalanced, strongly interacting Fermi Gases. Shown is the relaxation time of the spin-dipole mode in a strongly interacting, trapped Fermi gas, as a function of the reduced temperature $T/T_{F,up}$, where $T_{F,up}$ is the Fermi energy of the majority spin up Fermi sea. At high temperatures, the classical prediction (dashed line) produces a good description of the data, whereas at low temperatures, Pauli pressure leads to a strong reduction of the relaxation time. The solid line is a prediction for the homogeneous gas.

3. Strongly Interacting Isotopic Bose-Fermi Mixture Immersed in a Fermi Sea

Cheng-Hsun Wu, Ibon Santiago, Jee Woo Park, Peyman Ahmadi, Martin W. Zwierlein

PRA **84**, 011601(R) (2011)

We have created a triply quantum degenerate mixture of bosonic 41K and two fermionic species, 40K and 6Li. The boson is shown to be an efficient coolant for the two fermions, spurring hopes for the observation of fermionic superfluids with imbalanced masses. We observe multiple heteronuclear Feshbach resonances, in particular a wide s-wave resonance for the combination 41K-40K, opening up studies of strongly interacting isotopic Bose-Fermi mixtures. For large imbalance, we enter the polaronic regime of dressed impurities immersed in a bosonic or fermionic bath.

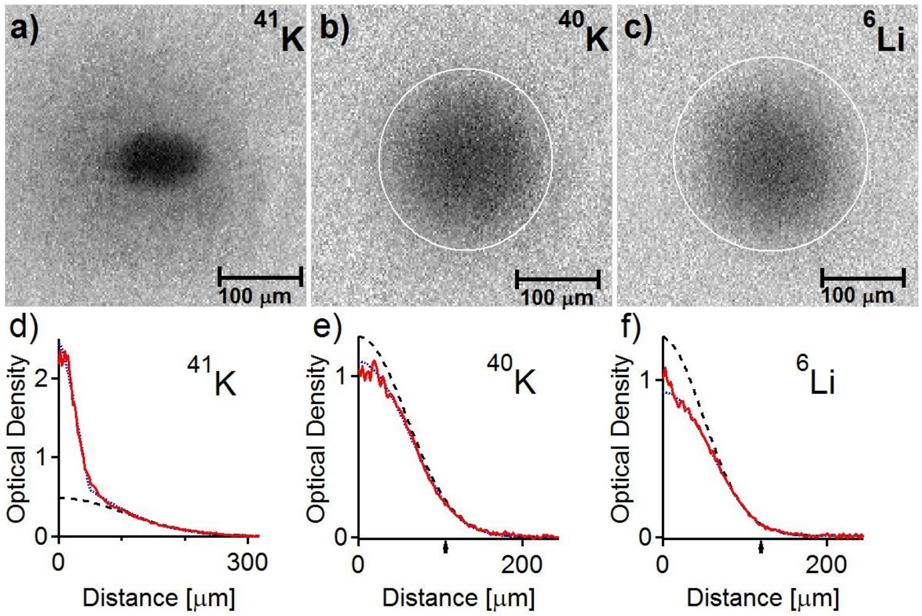

Figure 3 Triple degenerate mixture of ^{41}K, ^{40}K and ^{6}Li. a)-c) show absorption images of the three species, while d)-f) show azimuthally averaged optical densities. The dashed line is a Gaussian fit to the wings of the clouds, showing that each cloud is degenerate.

4. A localized magnetic impurity in a fermionic superfluid

Bound states of a localized magnetic impurity in a superfluid of paired ultracold fermions

Eric Vernier, David Pekker, Martin W. Zwierlein, Eugene Demler

Phys. Rev. A 83, 033619 (2011)

We consider a localized impurity atom that interacts with a cloud of fermions in the paired state. We develop an effective scattering length description of the interaction between an impurity and a fermionic atom using their vacuum scattering length. Treating the pairing of fermions at the mean-field level, we show that the impurity atom acts like a magnetic impurity in the condensed matter context, and leads to the formation of a pair of Shiba bound states inside the superconducting gap. In addition, the impurity atom can lead to the formation of deeply bound states below the Fermi sea.

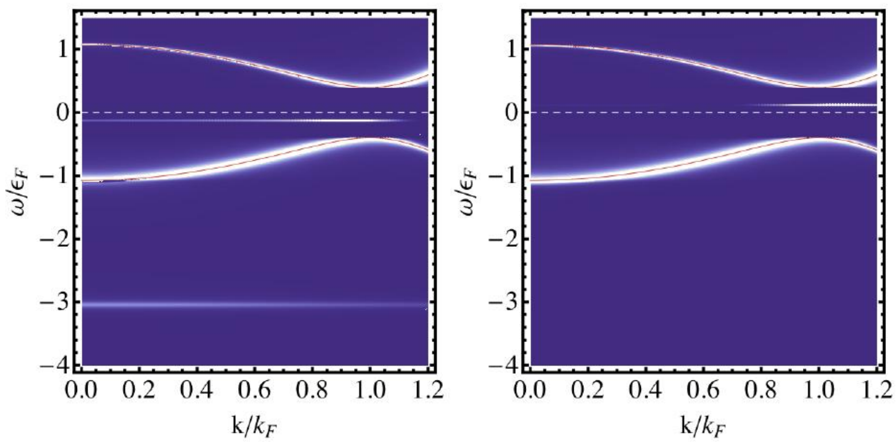

Figure 4 Impurity induced correction to the spectral function of the spin up atoms (left) and spin down atoms (right) as a function of momentum and frequency. The dashed line indicates the position of the Fermi energy. Both spectra show a depletion of spectral weight along the dispersion curve of the clean system indicated by the red line. The spin up spectrum (left) shows an under-sea bound state at $\omega = -3\ E_F$, as well as a Shiba state at $\omega = -0.13\ E_F$. The spin down spectrum only shows a Shiba state at $\omega = +0.13\ E_F$.

5. Competition between pairing and ferromagnetic instabilities

David Pekker, Mehrtash Babadi, Rajdeep Sensarma, Nikolaj Zinner, Lode Pollet, Martin W. Zwierlein, Eugene Demler

Phys. Rev. Lett. 106, 050402 (2011).

We study the quench dynamics of a two-component ultracold Fermi gas from the weak into the strong interaction regime, where the short time dynamics are governed by the exponential growth rate of unstable collective modes. We obtain an effective interaction that takes into account both Pauli blocking and the energy dependence of the scattering amplitude near a Feshbach resonance. Using this interaction we analyze the competing instabilities towards Stoner ferromagnetism and pairing.

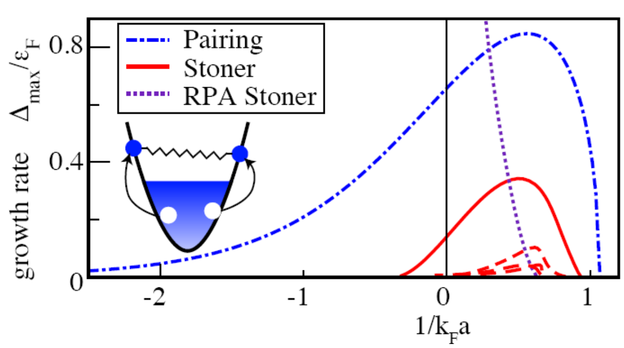

Figure 5 Growth rate of the pairing and Stoner ferromagnetic instabilities after a quench as a function of the final interaction strength $1/k_Fa$. The Stoner mechanism simultaneously occurs in multiple channels, the most unstable of which is shown as the solid line. Pairing, however, is the dominant instability, thus excluding the observation of Stoner Ferromagnetism.

Publications

Journal Articles, Published

1. Cheng-Hsun Wu, Ibon Santiago, Jee Woo Park, Peyman Ahmadi, and Martin W. Zwierlein, *Strongly Interacting Isotopic Bose-Fermi Mixture Immersed in a Fermi Sea*
PRA 84, 011601(R) (2011)

2. Ariel Sommer, Mark Ku, and Martin W. Zwierlein,
Spin Transport in Polaronic and Superfluid Fermi Gases
New J. Phys. 13, 055009 (2011)

IOP Select   Focus on Strongly Correlated Quantum Fluids

3. Ariel Sommer, Mark Ku, Giacomo Roati, and Martin W. Zwierlein,
Universal Spin Transport in a Strongly Interacting Fermi Gas
Nature 472, 201-204 (2011), arXiv:1101.0780 (2011)
See accompanying Nature News&Views by John Thomas

Physics Today   New Scientist   MIT News

4. Eric Vernier, David Pekker, Martin W. Zwierlein, and Eugene Demler,
Bound states of a localized magnetic impurity in a superfluid of paired ultracold fermions

Phys. Rev. A 83, 033619 (2011)

5. D. Pekker, M. Babadi, R. Sensarma, N. Zinner, L. Pollet, M. W. Zwierlein, and E. Demler,
Competition between pairing and ferromagnetic instabilities in ultracold Fermi gases near Feshbach resonances,

Phys. Rev. Lett. 106, 050402 (2011).

Invited Talks at Conferences

1. *Universal Spin Transport in Strongly Interacting Fermi Gases.*
Nordita program "Quantum solids, liquids, and gases", Stockholm, Sweden, 8/11/2010
2. *Universal Spin Transport in Strongly Interacting Fermi Gases.*
KITP Conference "Frontiers of Ultracold Atoms and Molecules", Santa Barbara, CA, 10/11/2010
3. *Universal Spin Transport in Strongly Interacting Fermi Gases.*
Nordita conference "Frontiers of Condensed Matter Physics", Stockholm, Sweden, 1/6/2011
4. *Universal Spin Transport in Strongly Interacting Fermi Gases.*
ERATO Macroscopic Quantum Control Conference on Ultracold Atoms and Molecules, Tokyo, Japan, 1/24/2011
5. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
APS March Meeting 2011, Dallas, Texas, 3/24/2011
6. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
ESF-IFRAF Fermix meeting, Paris, France, 4/14/2011

7. *Strongly Interacting Isotopic Bose-Fermi Mixture Immersed in a Fermi Sea.*
   3rd International Workshop on ultracold atoms/molecules
   Hsinchu, Taiwan, 4/30/2011 (talk by C.-H. Wu)
8. *Universal Spin Transport in a Strongly Interacting Fermi Gas.*
   INT Symposium: Fermions from Cold Atoms to Neutron Stars: Benchmarking the Many-Body Problem, Seattle, WA, 5/18/2011
9. *Universal Thermodynamics across the Superfluid Transition in a Strongly Interacting Fermi Gas.*
   INT Symposium: Fermions from Cold Atoms to Neutron Stars: Benchmarking the Many-Body Problem, Seattle, WA, 5/18/2011
10. Universal Thermodynamics across the Superfluid Transition in a Strongly Interacting Fermi Gas.
    Workshop on Frontiers in Ultracold Fermi Gases, Trieste, Italy, 6/8/2011
11. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
    Multiflavour strongly correlated quantum gases, Hamburg, Germany, 6/24/2011

Invited Talks at Colloquia and Seminars

1. Universal Thermodynamics and Spin Transport in Strongly Interacting Fermi Gases.
   Nuclear and Particle Theory Seminar, MIT Center for Theoretical Physics, Cambridge, MA, 2/14/2011
2. Universal Spin Transport in Strongly Interacting Fermi Gases.
   Atomic Physics Seminar, Cambridge, UK, 10/22/2010

Contributed Talks by Group Members at Conferences

1. Triply degenerate quantum mixture of 41K, 40K and 6Li.
   APS March Meeting 2011, Dallas, Texas, 3/23/2011
2. H4.00002: Revealing the superfluid phase transition in strongly interacting Fermi gases in a precision measurement of the equation of state.
   DAMOP 2011, Atlanta, Georgia, 6/15/2011
3. N5.00001 : Universal Spin Transport in Strongly Interacting Fermi Gases.
   DAMOP 2011, Atlanta, Georgia, 6/16/2011
4. P1.00007: Many body effects in a widely tunable Bose-Fermi mixture.
   DAMOP 2011, Atlanta, Georgia, 6/16/2011
5. P1.00003: Triply degenerate quantum mixture of 41K, 40K and 6Li.
   DAMOP 2011, Atlanta, Georgia, 6/16/2011
6. Universal Thermodynamics across the Superfluid Transition in a Strongly Interacting Fermi Gas.
   19th Particles & Nuclei International Conference (PANIC 2011), Cambridge, MA, 7/24/2011
7. Universal Spin Transport in a Strongly Interacting Fermi Gas.
   19th Particles & Nuclei International Conference (PANIC 2011), Cambridge, MA, 7/24/2011

Honors and Awards

Martin Zwierlein:
Jonathan Allen Junior Faculty Award, RLE, MIT, 2010
Young Investigator Award, Air Force Office of Scientific Research, 2010
Young Investigator Award, Office of Naval Research, 2010
Young Faculty Award, Defense Advanced Research Projects Agency, 2010
Presidential Early Career Award for Scientists and Engineers, Office of Science and Technology Policy Executive Office of the President, 2010
David and Lucile Packard Foundation Fellowship, 2010 – current
Silverman Family Career Development Chair, 2011 - current

A. Sommer received the Martin Deutsch Prize for Excellence in Experimental Physics from the MIT Physics Department